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Seaports and climate change - Impacts and adaptation options

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Abstract:
Due to their location at the intersection between sea and land, marine facilities are most vulnerable to various climate change impacts, but restrictions for the management of climate change challenges are evident like differences in planning horizons and lack of relevant information. As a basis for climate change adapted processes in port planning and operation a matrix containing possible climate change impacts and possibly affected port assets is presented. Furthermore, steps of a vulnerability analysis of seaports against climate change effects are described and the sensitivity of specific port assets to climate change effects as well as possible adaptation measures are exemplified.

Ports maritimes et changement climatique Impacts et mesures d'adaptation

Résumé :
En raison de leur emplacement à l'interface entre mer et terre, les installations marines sont les plus vulnérables aux divers impacts liés au changement climatique, mais les limites dans la gestion des défis climatiques sont évidentes comme les différences dans la planification à long terme et le manque d'informations pertinentes. Comme élément de référence pour les processus adaptés aux changements climatiques dans la planification et l'exploitation des ports, une matrice présentant les impacts possibles du changement climatique et les éventuels biens portuaires affectés est présentée. En outre, les étapes d'une analyse de la vulnérabilité des ports maritimes contre les effets du changement climatique sont décrites et la sensibilité des biens portuaires spécifiques aux effets du changement climatique ainsi que les mesures d'adaptation possibles sont illustrées.
Mots clés:
Changement climatique, Vulnérabilité, Exposition, Sensibilité, Capacité d'adaptation, Mesures d'adaptation, Ingénierie portuaire, Structures maritimes

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1. Introduction

Seaports play a major role in the seaborne transport system, being the interface between transport, storage and production as well as different transportation modes like transshipment, inland navigation, railway and road transportation. Climate change bears the potential to impact technical infrastructure significantly and persistently. The effects will probably be widespread and costly in contrast to influences of regionally and temporary acting extreme weather conditions. Therefore, early involvement of climate change aspects in planning processes is important in order to relieve or avoid expected resource constraints.

Due to their location at the intersection between sea and land, marine facilities are most vulnerable to changes of all water related parameters like mean relative sea level, storm water levels, wind waves and swell, tidal regime, sedimentation rates, waterborne immigration of species, water salinity and acidity. Furthermore, seaports can also be affected directly by temperature, precipitation and wind changes with respect to e.g. cooling system energy demands, terminal pavement durability and storm-water drainage system capacity, empty container storage heights etc. Climate change will have an influence on all of these aspects, as the following examples illustrate:

- Poor subsoil conditions often require extensive foundation works. A link between climate and subsoil bearing capacity exists especially in permafrost areas, where thawing may result in severe foundation problems.
- Sea level rise may necessitate the relocation of facilities or expensive protection measures not only on terminals and storage areas but also with respect to road and railway links.
- Increasing occurrence frequency of extreme sea states may increase the operational risks of existing harbor facilities and infrastructures, which were designed and built based on historical observations.

Already today, significant climate changes are observed both on global and regional scale, and increased changes are anticipated in the mid- and long-term. Because of their sensitivity to changes in mean sea water levels as well as extreme weather events, seaports need to be prepared to adapt access channels, terminals, infrastructure and facilities in order to be able to successfully operate in future. Therefore, a matrix containing possible climate change impacts and possibly affected port assets will be presented, which can be used by port planners and port authorities as a basis for climate change adapted processes in port planning and operation. Furthermore, examples of possible climate change adaptation measures in ports will be given.

2. Climate change sensitivity and adaptive capacity analyses for seaports

It is difficult to make general statements on the vulnerability of seaports to climate change. In some cases, already today climate change related problems in seaports are obvious, like changing properties of permafrost soils and related foundation problems in high latitudes. Other climate change impacts will influence port planning and operation only in a later stage because in short and mid-term (*i.e. short-term: up to 15 years, mid-term: up to 30 years, long-term: up to 100 years*) only minor effects of climate change are effective or the vulnerability of the system 'seaport' to the respective climate trend is only marginal. Additionally, ports located at the open sea have to bear other loads than estuary or lock-separated ports and the sensitivity of cargo handling with respect to wind and wave loads differs with cargo type.

Vulnerability can be described by three components: exposure, sensitivity and adaptation capacity. The determination of the exposure of a specific port has to be based on an analysis of climate change impacts on a regional scale. Then, a sensitivity analysis and an adaptive capacity analysis have to be conducted for the port as a whole or for particular port assets. Combining the findings of these analyses will result in a quantification of the vulnerability of the seaport to climate change impacts.

2.1 Sensitivity analysis

A sensitivity analysis will examine the aspects listed in table 1.

Table 1. Aspects of a sensitivity analysis.

1.	*System of interest, e.g. breakwater, quay wall, flood protection, terminal infrastructure and superstructure, drainage system, storage area, hinterland connection*
2.	*System planning parameters, e.g. functional and structural design, operation characteristics, lifecycle aspects, state-of-the-art aspects*
3.	*Current relevant climate conditions affecting the system in the planning area, e.g. cold and long-lasting winters, hot summers, often and intensive storm surges, heavy precipitation*
4.	*Existing stresses under current climate conditions, e.g. coastal erosion problems, high sedimentation rates, flooding, extended operation downtime due to wave action, limitations to port operation due to high algae growth rates in spring and summer*
5.	*Projected change of relevant climate conditions (including climate conditions that will become relevant due to projected changes) in the short-, mid- and long-term, e.g. rise of air and water temperature, more intense storm surges, sea level rise, changes of wind direction distribution*
6.	*Projected impacts of climate change without preparedness action, e.g. foundation and structural problems, increase in port operation down-time, lack of terminal or storage space, increase in flooding damages*
7.	*Degree of system sensitivity to climate change, e.g. high, moderate, low, uncertain*

2.2 Adaptive capacity analysis

An adaptive capacity analysis will examine the aspects listed in table 2.

Table 2. Issues of an adaptive capacity analysis.

1.	*System of interest, e.g. breakwater, quay wall, flood protection, terminal infrastructure and superstructure, drainage system, storage area, hinterland connection*
2.	*System planning parameters, e.g. functional and structural design, operation characteristics, lifecycle aspects, state-of-the-art aspects*
3.	*Ability of the system to cope with climate change effects, e.g. changes in the tidal regime accompanied by stronger tidal currents may lead to scour deepening at existing quay walls, yet being in a range not affecting the structural strength of the construction*
4.	*Obstacles to a system's ability to cope with climate change effects, e.g.* *–Legal regulations, e.g. national borders limiting a required port extension / relocation to adopt to new climate situations; environmental regulations restricting dredging works required to balance higher sedimentation rates due to changes in tidal regime in an estuary* *–Limited management flexibility due to a high number of competing requirements, like navigation and port services, flood control, irrigation supply, water quality, protection of endangered species, cooling purposes, recreation* *–Limited management flexibility due to geographic situation, e.g. relocation in case of significant sea level rise may not be possible because of a hilly hinterland*
5.	*Existing stresses and constraints limiting the system ability to accommodate climate changes, e.g. existing overload with respect to e.g. structural stability or flooding levels, lack of terminal or storage space, lack of financial means*
6.	*Effectivity and success of efforts already undertaken to deal with climate changes (or other challenges), e.g. analysis of structural weak points, managing plans*

3. Climate change impacts on seaports

Selected phenomena of climate change and their possible opportunities and risks for seaports are described in table 3. In some cases, a potential improvement or worsening of the situation can only be assessed in a case-by-case manner. For example, changes in the wind direction distribution may reduce or increase sedimentation in the port access channel and in harbor basins. Furthermore, a change of one parameter due to climate change may also result in changes of other parameters not directly linked to climate change impacts. For example, an increase in sea level due to climate change potentially enlarges the water depth in an estuary serving as a port access but also influences the tidal regime, which may lead to larger quantities of sediment in the access channel and eventually smaller water depths. Often quite complex process chains have to be considered in the assessment of climate change impacts.

Table 3. Selected phenomena of climate change and possible impacts on seaports.

Phenomenon and direction of trend	***Possible impacts on seaports***
Temperature	
Increase in annual mean air temperature	***Risks:*** *More high temperature related downtimes (low latitude zones)* *Decline of extent of permafrost soils leading to foundation and erosion problems (high latitude zones)* *Immigration of new species potentially leading to higher deterioration rates of port infrastructures and problems in port operation*
Increase in annual mean water temperature	***Opportunities:*** *Less ice related downtimes (high and middle latitude zones)* *More ice-free ports and longer shipping seasons in high latitudes* ***Risks:*** *Growth rate increases of waterborne species* *Immigration of new species potentially leading to higher deterioration rates of port infrastructures and problems in port operation*
Increase in extreme high air temperatures	***Risks:*** *Increase in power consumption for cooling systems (e.g. reefer containers and refrigerated warehouses)* *Higher deterioration rates of pavements (e.g. terminal surfaces)* *Increase in stress on temperature sensitive structures made of metal (e.g. container handling cranes, warehouses)* *Increase in heat related disruptions in the hinterland traffic*
Increase in extreme high water temperatures	***Risks:*** *Restrictions to port related operations (e.g. maintenance dredging) due to low oxygen content in warmer water* *Increase in production downtime in port located industrial plants with water cooling systems due to exceedance of water temperature threshold values*
Decrease in number of days with sub-zero temperatures	***Opportunities:*** *Less low temperature related downtimes (high and middle latitude zones)* *More ice-free ports and longer shipping seasons in high latitudes* ***Risk:*** *Decline of the extent of permafrost soils leading to foundation and erosion problems (high latitudes)*
Precipitation	
Increase in intensity of heavy rainfall events	***Risks:*** *Increase in heavy rain fall related port operation downtime* *Increase in flood risk due to high water levels in the hinterland* *Increase in storm-water drainage system capacity overload* *Increase in deterioration rates of storm-water drainage systems* *Increase in storm-water related disruptions of the hinterland traffic*
Increase in the amount of annual rainfall	***Opportunity:*** *Improvement of inland navigation conditions during low water season due to higher discharge rates and consequently higher water levels in inland rivers* ***Risks:*** *Worsening of inland navigation conditions during high water season due to higher discharge rates and consequently higher water levels* *Worsening of inland navigation conditions during high water season due to higher discharge rates and consequently less overhead clearance below bridges* *Worsening of inland navigation conditions during high water season due to increased flow velocities caused by higher discharge rates* *Higher water content in soils and subsequently slope stability problems*
Decrease in the amount of annual rainfall	***Opportunity:*** *Reduction of inland navigation downtime related to high water levels or high discharge rates* ***Risks:*** *Worsening of inland navigation conditions during low water season due to lower discharge rates and consequently lower water levels in inland rivers* *Worsening of water quality in inland rivers during low water season due to lower discharge rates; consequently, possible restrictions in maintenance works*
Wind	
Increase in frequency of storm events	***Risks:*** *Increase in wind related port operation downtime* *Increase in high water level related port operation downtime* *Increase in wave related port operation downtime* *Increase in storm related disruptions in the hinterland traffic* *Increase in coastal erosion rates especially at sandy coasts*
Increase in intensity of extreme storm events	***Risks:*** *Increase in storm surge related damages to port infra- and superstructure* *Increase in port operation downtime related to infra- and superstructure repair* *Decrease in allowable storage heights, especially on empty container storage yards – increase in required storage area* *Increase in storm related disruptions of the hinterland traffic* *Increase in coastal erosion rates esp. at sandy coasts*

Phenomenon and direction of trend	***Possible impacts on seaports***
Change of wind direction distribution	***Opportunities:*** *Potential decrease in water level, wind, wave related stresses as well as sedimentation rates, depending on the individual case* ***Risks:*** *Potential increase in water level, wind, wave related stresses as well as sedimentation rates, depending on the individual case*
Sea level	
Increase in mean relative sea level	***Opportunity:*** *Increase in water depths in port access channels and harbor basins* ***Risks:*** *Increase in flood levels in extreme events (storm surges)* *Increase in coastal erosion rates especially at sandy coasts* *Increase in wave stresses at quay walls, breakwaters, extended wharfs and other port infrastructure during mean and high-water levels* *Decrease in overhead clearance below bridges and port cranes*
Changes of the tidal regime in estuaries due to changes in mean relative sea level	***Opportunities:*** *Increase in water exchange rate and consequently increase in water quality in case of higher tidal range* *Potential increase in the erosive potential of the ebb stream velocities relative to flood stream velocities in case of higher tidal range resulting in less sedimentation* ***Risks:*** *Potential erosion around bridge footings in case of higher tidal range and subsequent higher current velocities* *Temporarily higher sedimentation rates due to upstream shift of the tidal boundary and the brackwater zone* *Potential long-lasting increase in sedimentation rates due to tidal pumping effects (increasing flood stream velocities relative to ebb stream velocities)* *Immigration of new species potentially leading to higher deterioration rates of port infrastructures and problems in port operation*
Water chemistry	
Increase in salinity	***Opportunity:*** *Potential decrease in growth rate of domestic species* ***Risks:*** *Increase in the water's corrosive potential to steel and concrete structures* *Potential immigration of new species* *Potential increase in growth rate of domestic species*
Decrease in salinity	***Opportunities:*** *Decrease in the water's corrosive potential to steel and concrete structures* *Potential decrease in growth rate of domestic species* ***Risks:*** *Potential immigration of new species* *Potential increase in growth rate of domestic species*
Acidification	***Risk:*** *Increase in the water's corrosive potential to steel and concrete structures*
Species	
Increase in growth rate of domestic species	***Risks:*** *Potential increase in harmful species population leading to deterioration of construction material* *High amount of organism in conjunction with lack of oxygen leading to high sedimentation rates*
Immigration of new species	***Risk:*** *Potential increase in harmful species population leading to deterioration of construction material*

4. Climate change sensitivity of port assets and adaptation measures

Accurate predictions of regional climate change impacts on design and operation of seaports are currently not available and will be difficult to attain in future. Nevertheless, as constructions designed today may be subject to changing loads due to climate change during their lifetime, considering climate change predictions is essential already now. Design loads like extreme water levels and wave heights are often defined by statistical return periods, e.g. 50-year wave height or 100-year high-water level. Climate change impact may change a former 100-year return period to a 50- or 20-year-return period with the effect of a significant increase in the failure risk of the construction. Therefore, consideration of climate change effects in port planning and investment schedules should rather start now than tomorrow. As accurate regional climate change predictions are not yet available, probable scenarios have to be defined as a planning tool for today's port construction and future port operation.

The adaptation of seaports to climate change requires proper vulnerability analysis based on sensitivity and adaptive capacity analyses of specific port systems referring to locally anticipated climate change effects. The following four port asset categories can be distinguished:

- Basic port infrastructure like maritime access channel, port entrance, protective works and hinterland connection
- Operational port infrastructure like inner port channels and port basins, quay walls and port internal traffic systems
- Port superstructure like pavements, drainage system, stacking areas, tank farms, silos, and warehouses
- Port equipment like ship and shore handling equipment, as well as cargo handling and storage equipment

Within the present paper, general remarks will be given on the port assets maritime access channel, breakwaters and jetties, and hinterland connections by roads.

4.1 Maritime access channel

The design of the maritime access channel regarding length, width and run is strongly dependent on the port location with respect to open sea, estuary or waters with large tidal range. Often, water depth in the port access channel is not sufficient for larger vessels entering the port and the required water depth has to be guaranteed by rock drilling and blasting or dredging (both investment and maintenance dredging) as well as supporting constructions like groins and training structures, the latter being mainly used in estuary ports.

Two general categories summarize key characteristics of maritime access channels:

- Channel layout, i.e. plan view with straight and curved sections
- Channel cross section characterized by depth, width, side slopes, and lateral restriction or non-restriction

In general, the layout and dimension of maritime access channels are determined as multiples of the design ship's beam and draft, taking into account additional factors like:

- Vessel traffic characteristics, e.g. traffic mix and traffic density with respect to one-way or two-way traffic; vessel's length; vessel's velocity with respect to squat; overall vessel maneuverability; dangerousness of transported goods
- Environmental factors, e.g. tide, wind, waves, and currents
- Structures, e.g. bridges with respect to their clearance height as well as lateral constructions like piers, training structures, and groins

In estuaries, climate change risks with respect to maritime access channels are expected mainly due to an increase in sedimentation and thus a decrease in water depth. Changes in sediment transport are generally difficult to predict and countermeasures may be designed rather in a reactive manner and hardly in advance. Shorter maintenance dredging intervals are the most common countermeasure. Depending on the result of a detailed investigation of the hydrology and sedimentology, the construction of training structures influencing currents may be useful.

The entrance channel of ports at the open sea is generally less vulnerable to climate change effects as sea level rise and resulting larger water depths bear more opportunities than risks.

4.2 Breakwaters and jetties

Breakwaters and jetties border the port basin and entrance from the sea or estuary serving as a protection against waves and currents. In some cases, the inner side of the construction may be used as a berthing place.

The orientation and width of the entrance opening between the breakwaters and jetties must fulfill two opposing demands, which have to be carefully balanced:

- Considering navigational aspects, the port entrance should be as wide as possible
- For protection of the inner port and the entrance area against waves, currents, and sedimentation the port entrance should be as narrow as possible

The entrance should be preferably oriented in such a way that prevailing winds blow towards or opposite entering vessels as transverse winds and waves may create difficult navigational conditions. Furthermore, entrance jetties should not end in the highly turbulent zone of breaking waves.

Different types of breakwaters or jetties can be distinguished as follows:

- Sloping or rubble-mound breakwater
- Vertical breakwater
- Composite breakwater
- Special breakwaters like piled or floating breakwaters which are suitable in seaports only to a limited extend due to their high wave transmission ratio

Generally, the following loads have to be assessed within the design process of sloped or vertical breakwaters:

- Design water depth
- Design wave parameters like wave height, wave period and wave angle relative to the construction

Depending on type, shape and transmissibility of a breakwater, wave forces, wave run-up and overtopping as well as wave transmission and reflection have to be assessed to determine the breakwater's height and layout. The latter should consider armor unit weight and layer thicknesses in case of rubble mound breakwaters and overall stability in case of vertical breakwaters.

Looking at overtopping rates, a simple arithmetic example can illustrate the problem. According to EUROTOP (2007), the mean overtopping rate at a vertical structure with a crest freeboard of R_c=3.0 m and a design wave height of H_s=1.0 m is q=0.6 l/(s*m).

Considering a sea level rise of +0.5 m the mean overtopping rate would increase to q=1.4 l/(s m) and to q=3.4 l/(s m) for a sea level rise of +1.0 m, respectively. Since damages may occur at facilities placed 5 to 10 m behind the protection line if q≥1 l/(s m), the increase in mean overtopping rates may result in significant utilization restriction or even structural damages.

As breakwaters are long-living and costly structures, the consideration of anticipated climate change effects is highly recommended in the design of new structures. Increasing wave loads have to be considered in the determination of armor unit weights of sloped constructions or component weight and stability of vertical constructions. It is recommended to conduct a sensitivity analysis of possible incident wave heights and periods dependent on wave direction to check if possible changes in the wind direction distribution may lead to significant increases of wave loads in the port entrance and at terminals.

Rising water levels have to be encountered by heightening the crest level or by arrangements offering a later heightening of the crest level, like wider bases and stronger foundations.

4.3 <u>Hinterland connection by roads</u>

Hinterland transportation consists of a mix of road freight, rail, and inland waterway transport. As hinterland connections play a crucial role in the freight network of seaports, it is of prime importance to offer a high productivity and a permanent operability. The productivity is strongly dependent on the number of traffic lanes and railtracks with respect to roads and rails and on the width and depths of the fairway with respect to inland waterways. The operability depends on the stability and resistance of the construction material against loads as well as on sedimentation processes in waterways.

Road infrastructure is a long-lived investment. Roads typically have design lives of 20 to 40 years and bridges of 100 years. Road maintenance works include cleansing and restoring of surface and sub-surface drainage systems as well as surface rejuvenating.

Road constructions typically comprise a number of layers, consisting at least of surface layer, bedding layer, road-base, sub-base, capping layer, and plane. The materials of the surface layer as well as the road-base are generally bound in a less permeable matrix such as cement or bitumen. The layers of the road foundation can be made up of unbound granular material. Road pavements made up with a bituminous surface are flexible, whereas pavements made up of high strength concrete or reinforced concrete are rigid.

Mainly asphalt or cement is used as a matrix for the upper layers, since these materials are reliable and strong. Nevertheless, both materials have their advantages and disadvantages. One main difference is the durability, where concrete roads are more durable resulting in a longer life compared to asphalt roads. Concrete roads are less sensitive to oil leakages than asphalt layers and extreme weather conditions like heat and frost will result in lesser damage. Therefore, the maintenance cycle of concrete roads is longer than for asphalt roads. On the other hand, asphalt roads are easier to repair because a partly repair is possible as well as a re-layering. Furthermore, asphalt roads provide better safety for vehicles because of better skid resistance and provision of good traction. The choice of the surface material in a specific project requires a consideration of all of these aspects.

Roads connecting the hinterland of ports are loaded by heavy goods vehicle traffic as well as climatic conditions like severe frost, freeze-thaw cycles, excessive rainfall or extreme heat. Direct weather impacts on surface material are the following:

- High temperatures, both maximum temperature as well duration of high temperatures, are significant especially with respect to bituminous pavements leading to adverse effects on the hardness of the road surface, fatting up of the road surface as well as thermal expansion and contraction affecting the integrity of the road surface resulting in potholing, rapid loss of surface condition, and rutting
- Cycles of freezing and thawing can cause volume changes resulting in disaggregation effects within the road structure; climate change may even increase these effects because rising temperatures does not exclude the possibility of a greater extent of thawing and refreezing, possibly following a day and night pattern
- Changes in rainfall patterns can alter water balances and influence pavement deterioration
- Changes in temperature and rainfall patterns may interact where higher temperatures increase cracking, which amplifies the effects of increased rainfall
- Melting permafrost may lead to a destabilization of road beds

Beneath material aspects also road elevation plays an important role in port operation as flooding may close the transport route and lead to downtime. Higher mean sea levels and storm surge water levels as well as more intense wave exposure may lead to an increase in flood risk.

Most climate change impacts bear risks for roads. Considering climate change issues in road planning potentially will lead to significant cost reductions on the long run, allowing for longer maintenance intervals and longer lifetime of the structure as well as less downtime. Dependent on the project area, a more sophisticated road-bed, a more resistant road surface – e.g. made of concrete instead of asphalt - and a higher road elevation may be necessary to cope with climate change effects.

Special attention must be given to thawing processes of permafrost soils as permafrost serves as a foundation for most structures like roads, railways and buildings in the Canadian Arctic, Alaska, and Siberia. With the loss of permafrost, efforts and expenses for secure foundations in these regions will raise significantly.

5. Conclusions

Seaport infrastructure in general is characterized by long life spans, enforcing long-term planning horizons. Climate change issues may impact the construction and operation of seaports in manifold ways, with respect to navigation water levels, overhead clearances, sedimentation patterns, structural loads, material deterioration, etc. Therefore, early involvement of climate change aspects, especially in port planning processes of long living assets, is highly recommended.

In view of the immense damage potential of climate change impacts on port structures, an understanding and a consideration of the expected impacts of future climate change by port planners, port authorities, terminal operators and asset managers allows for considerable long-term cost savings. At the broad strategic level, forewarning experts and authorities will allow them to better prepare to deal with costly future effects.

Uncertainties in modeling climate change prospects are still significant, especially on regional and local scale, where currently mainly climate change tendencies are available. Furthermore, restrictions for the assessment and management of climate change challenges to seaports exist, like differences in planning horizons, lack of relevant information and treatment of uncertainty, limited climate change awareness amongst stakeholders, financial restrictions, and complexity of the decision-making process with respect to climate change issues.

General statements on the vulnerability of seaports to climate change are not possible. In some cases, already today climate change related problems in seaports are obvious, like changing properties of permafrost soils and related foundation problems in high latitudes. Other climate change impacts will influence port planning and operation only at a later stage, because in short and mid-term only minor effects are effective or the vulnerability of the system 'seaport asset' to the respective climate trend is only marginal. Additionally, ports located at the open sea have to bear other loads than estuary or lock-separated ports and the sensitivity of cargo handling with respect to wind and wave loads differs with cargo type.

The climate vulnerability of a seaport is defined by its exposure, sensitivity and adaptation capacity to climate change. The determination of the exposure of a specific port has to be based on an analysis of climate change impact scenarios on a regional scale. Locally relevant climate change scenarios have to be defined on the basis of existing global and regional findings. Considering climate change aspects in port planning always means the inclusion of uncertainties of climate change projections as well as changes in predictions, which will have to be accepted not only today but also in future. All planning must be done on the basis of scenarios including each a range of values of specific climate data like temperature, sea level rise, or rainfall intensity. The identification of current vulnerabilities like port downtime and/ or damages because of e.g. fog, extreme water levels or storms provides valuable indications to assess potential future key problems.

Adaptation measures in seaports with respect to climate change can be distinguished in active and reactive measures. Active measures are the appropriate solution for climate change sensitive port assets in case their expected lifetimes are long and a later adaptation to climate change impacts may be connected with a significant increase in costs. Examples of active measures are:

- Using heat resistant materials like concrete pavements instead of asphalt
- Using larger units in breakwater construction due to an anticipated increase in wave loads with respect to sea level rise and/or larger wind speeds
- Provision of enough space and strength for refitting flood protection measures at a later stage

Adaptation measures to climate change impacts can also be executed in a reactive way if this will lead to no significant increases in operational risks and costs. An example for a reactive measure is the shortening of maintenance dredging intervals in case an intensification of sedimentation in harbour entrance channels is observed.

Combining the analysis of vulnerabilities of specific port assets to climate change and the development of appropriate active or reactive adaptation measures an effective climate proof planning and operation procedure can be established in ports and harbors.

6. Reference

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